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REVIEW OF U.S. METEOROLOGICAL ROCKET NETWORK ACTIVITIES AND RESULTS

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Abstract: The more complete the picture became of the atmospheric circulation up to approximately 100000 ft, the greater was the desire to obtain data from higher levels. This desire became an urgent requirement after Scherhag's detection of the so-called explosive warming which seemed to start from levels higher than those attainable by balloons and to propagate downwards.

In order to obtain synoptic data from these higher levels, the balloon had to be replaced by small inexpensive rockets as instrument carriers. While these small meteorological rockets for operational use were being developed, representatives of various agencies within the United States, interested in upper air meteorological research, agreed to support and operate a synoptic meteorological rocket network. This network, which started with three stations in the fall of 1959, now consists of 11 stations which more or less regularly conduct synoptic rocket soundings to acquire wind and temperature data up to approximately 60 km. ARCAS and LOKI rockets are employed as sounding vehicles. During the first year of operation daily flights were carried out during the mid month of each season. Since the Spring of 1961, three flights per week throughout the year are scheduled.

Parallel with these routine ascents, theoretical and field experiments are conducted to improve the sounding system and to determine more accurately the errors of the various meteorological sensors. As a result of these synoptic meteorological rocket firings, it was possible to draw contour and wind maps for the United States and Canada for levels between 30 to 60 km. Plans are being made to extend the synoptic investigation to the level between 60 km to at least 100 km on atmospheric strata which, as pilot experiments have indicated, is very active dynamically.

Резюме: Чем яснее становилась картина атмосферной циркуляции, до высоты приблизительно 100.000 футов, тем сильнее возрастало желание получить данные с более высоких уровней. Это желание переросло в необходимость после того, как Шехарг обнаружил повышение температуры, которое начиналось на высотах, недостижимых для шаровзондов, и распространялось вниз. Для того чтобы получить синоптические данные с этих высоких уровней, шары зонды необходимо было заменить небольшими недорогими ракетами, которые могли бы служить носителями аппаратуры. В то время, когда создавались такие метеорологические ракеты, представители различных агенств Соединенных Штатов, заинтересованные в метеорологическом исследовании верхней атмосферы, согласились поддерживать и обслуживать сеть синоптических станций по запуску метеорологических ракет. Эта сеть, которая начала свое существование, осенью 1959 года с трех станций, состоит теперь из 11 станций, проводящих более или менее регулярные запуски метеорологических ракет, и получает данные о ветре и температуре приблизительно до 60 км. Используются ракеты АРКАС и ЛОКИ. В первый год работы в среднем месяце каждого сезона проводились ежедневные запуски. Начиная с весны 1961 г. программа предусматривает три запуска в неделю в течение всего года. Кроме этих программных запусков для усовершенствования системы зондирования и более точного определения ошибок различных метеорологических приборов проводятся запуски ракет для обеспечения теоретических и других экспериментальных задач. В результате запусков метеорологических ракет появилась возможность создания контурных карт и карт ветров над США и Канадой для высот от 30 до 60 км. Намечены планы расширения синоптических исследований, по крайней мере; до высоты 100 км, т.е. тех слоев атмосферы, которые обладают очень высокой динамической активностью.

1. Introduction

The exploration of the upper atmosphere with rockets in the United States regarding meteorological parameters started after World War II. At first, captured German V-2's were used for this purpose, and later American-built rockets like the Viking and the "workhorse" Aerobee. These firings

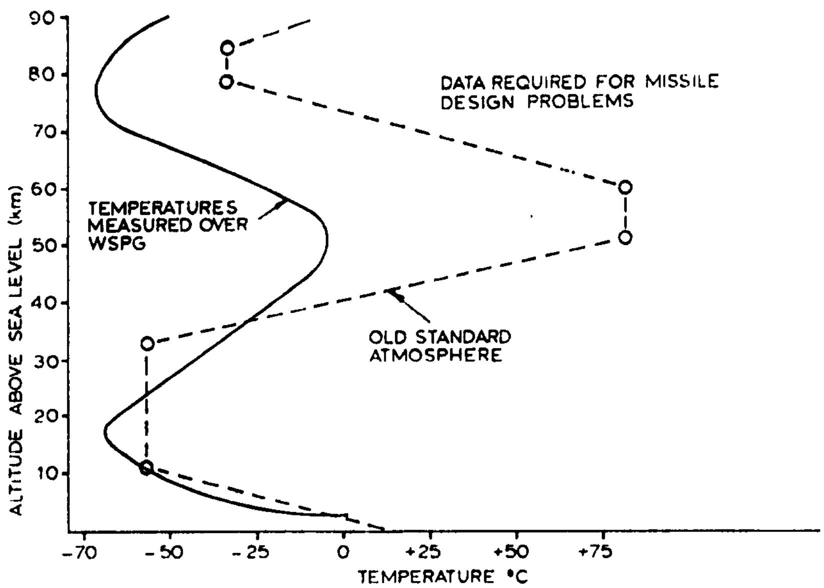

Fig. 1. Comparison between the old NACA standard atmosphere and rocket data obtained by the rocket-grenade experiment at the White Sands Missile Range.

were carried out at the White Sands Missile Range, measuring temperature, pressure, density, and wind composition up to approximately 100 km. The results of these firings demonstrated the great importance of such direct measurements of the meteorological parameters at the altitudes which cannot be reached by balloons. As can be seen in fig. 1, the actual mesopeak tem-

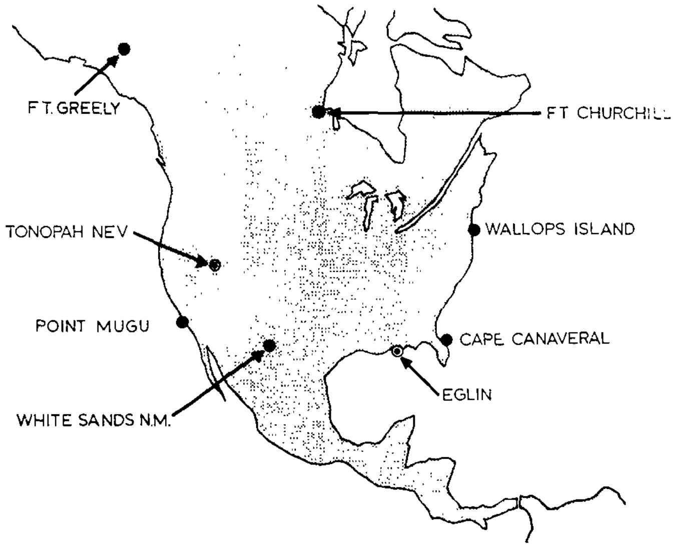

Fig. 4. Stations of the Meteorological Rocket Network.

Fig. 6. Loki II rocket ready for insertion into the launcher.

Fig. 8. Arcas rocket ready for insertion into the launcher, which for this purpose is in the horizontal position.

Fig. 10. Bead thermistor for use in rocketsondes compared with human hair seen above the bead.

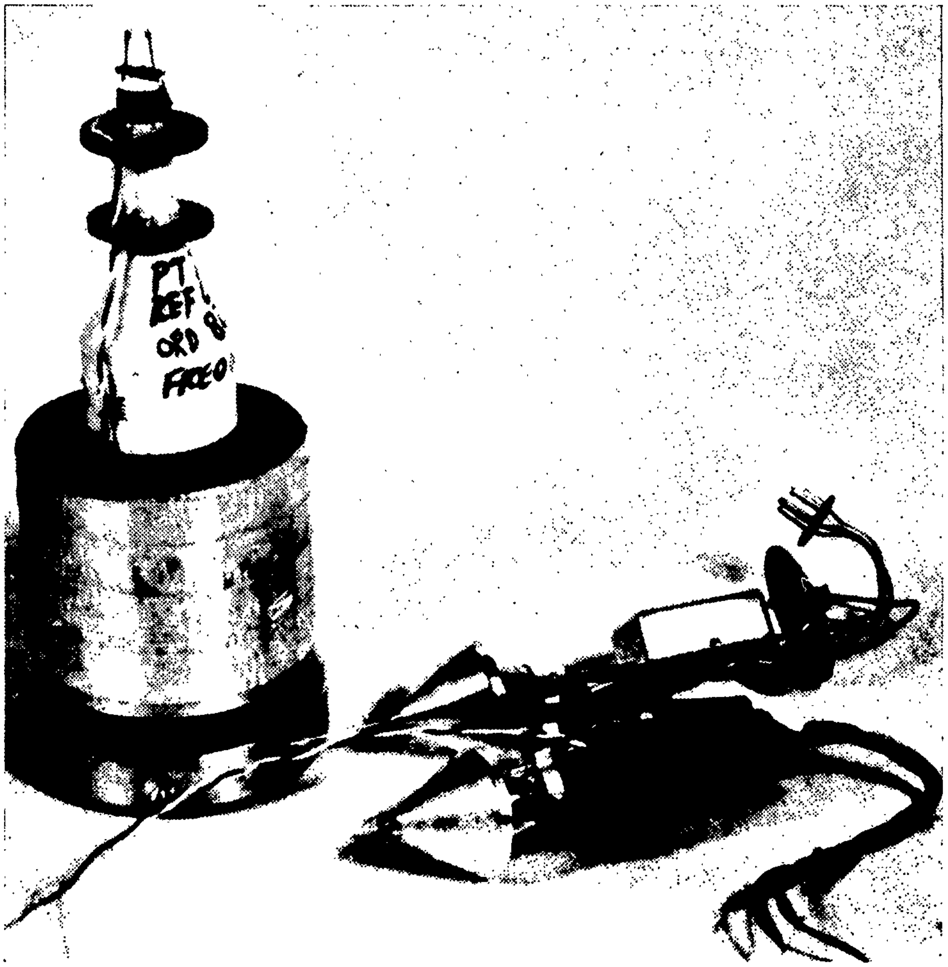

Fig. 9. The Gamma rocketsonde for the Arcas rocket.

Fig. 13. Robin balloon as developed under contract by the Air Force Cambridge Research Laboratory.

perature at 30° latitude, for example, is in the vicinity of 0° C and not around 70° C as indicated by the NACA Standard Atmosphere, which was established from indirect measurements and which, until 1951, was used by rocket and missile designers as standard. While subsequent measurements at

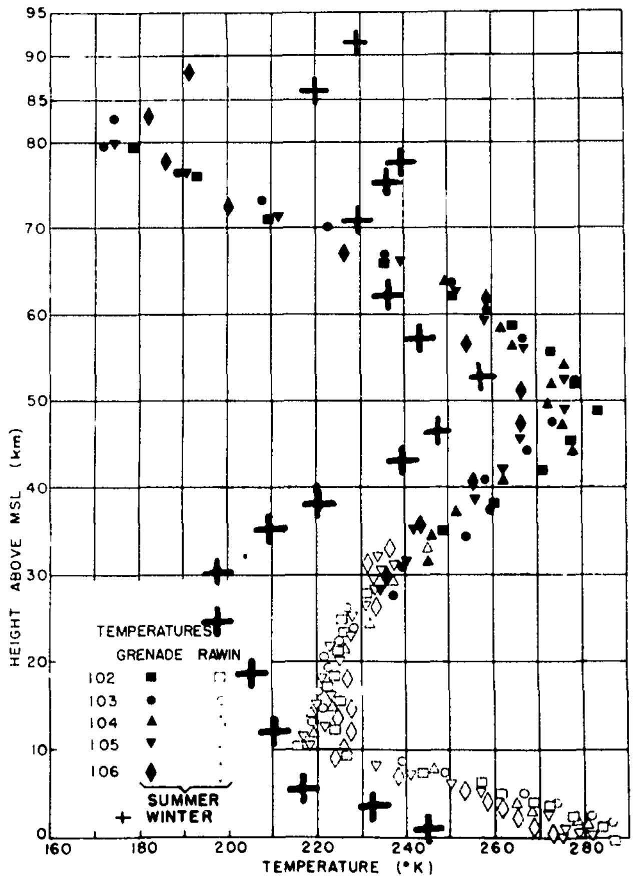

Fig. 2. Summer and approximate mean winter temperatures over Fort Churchill, Canada, as determined by the rocket-grenade experiment according to Stroud, *et al.*

White Sands Missile Range confirmed these results, it seemed to be very desirable to find out whether or not the same results would be obtained in more northern latitudes. The IGY offered an excellent opportunity to carry out such measurements at Fort Churchill, Canada. The results of these measurements yielded another surprise; namely, that the temperatures in winter between 70 and 90 km are much warmer than in summer (fig. 2). The average difference reached a maximum of 60 to 70° C according to the data collected by Stroud *et al.*[1]. Dr. Nordberg, in a subsequent paper in this symposium, discusses more extensively these conditions above 60 km.

The IGY rocket series also indicated that in the regions above the reach of balloons the atmospheric circulation is not always westerly in winter and easterly in summer, but that these predominant wind regimes may, from time to time, be severely disturbed. These firings indicated, furthermore, that the very interesting explosive warmings in the upper stratosphere and lower mesosphere which has been discovered by Scherhag [2] in 1952, using balloons, occurred also at higher altitudes.

It was clear that, in order to explain these extremely interesting phenomena, the sporadic rocket ascents that had been carried out up to that time must be replaced by systematic synoptic rocket measurements at various locations. With this in mind, meteorologists of the United States interested in upper-air meteorological research met and decided to create a meteorological rocket network.

2. Organization of the Meteorological Rocket Network

All agencies which were approached to lend support to this undertaking responded enthusiastically. In order to cover all research and operational aspects in this endeavor, close cooperation and coordination of all concerned were necessary. Participating in the formation of the Meteorological Rocket Network were: the US Air Force, Army, Navy, National Aeronautics and Space Administration, the Weather Bureau, Rand Corporation, and Sandia Corporation. The cordination was established by the creation of two groups (fig. 3): the Joint Scientific Advisory Group (JSAG) of the Meteorological Rocket Network and the newly formed Meteorological Rocket Network Committee of the already existing Meteorological Working Group of the Inter Range Instrumentation Group (MRNC-MWG-IRIG).

The members of the first group are scientists engaged in upper-air meteorological research and in development of rocket instrumentation for upper-air research. The task of this group consists of designing experiments related to the network activities, performing error analysis of the various sensors, and analyzing the resulting data. It had also an advisory function, i.e., advising the second group, which consists of the meteorologists of the various proving grounds participating in the Meteorological Rocket Network. This second group is responsible for the operation of the network. It is the focal point for the transfer of information relative to the efficiency of the meteorological rockets and their procurement, as well as the formation of firing schedules, deployment of equipment, and initial dissemination of the data. The group

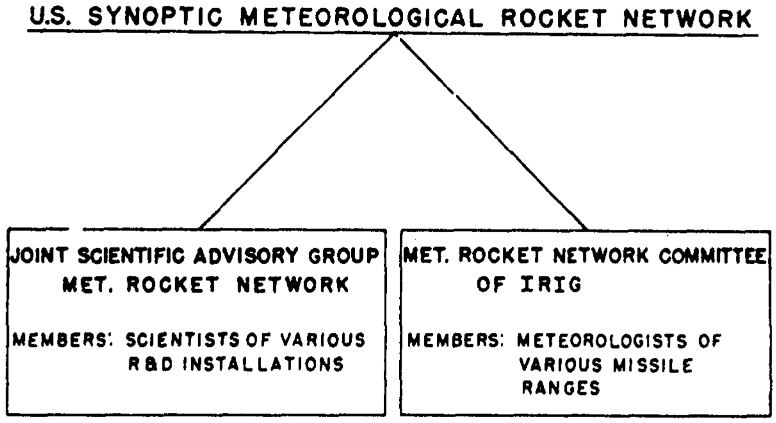

Fig. 3. Organization of the Joint US Meteorological Rocket Network.

has done an outstanding service to all upper-air meteorologists. This is particularly noteworthy since all these functions are carried out on a voluntary basis in a cooperative fashion.

Since the rocket ascents had to be carried out at rocket proving grounds, the stations indicated in fig. 4 were chosen as firing sites. A few firings have also been made at Eniwetok, Marshall Islands, and Hawaiian Islands.

Originally, daily firings during the midmonth of each season were scheduled. It was furthermore planned to carry out about six daily firings on a few days at stations like White Sands Missile Range and Tonopah which, because of the high elevation, would guarantee firings to at least 80 km for the investigation of tidal winds. Finally, it was intended to carry out several firings per day if interesting weather situations like the explosive warmings should occur.

After about $1\frac{1}{2}$ years of operation, the data collected suggested that it would be more advisable to make rocket ascents two or three times a week throughout the year rather than daily firings in the midmonth of each season. Accordingly, the schedule was changed. While all stations in fig. 4 plus the three stations in the Pacific Ocean participated in the synoptic network firings, it was often impossible to have simultaneous firings at all stations. This is understandable, considering the difficulties which occur in coordinating these firings with the various range facilities, plus the fact that the rockets as well as the instrumentation are still in a research and development status.

3. Instrumentation

It is evident that the idea of a synoptic rocket network as envisioned above could be realized only if much smaller rockets than V-2's and Aerobees could be made available. As seen in fig. 5, the research rocket development came a long way before it arrived at the Loki and Arcas rockets, which were used in the Meteorological Rocket Network. Both rockets reach altitudes in excess of 60 km, if fired from sea level at an angle of 85 degrees. The Loki (fig. 6), with booster and dart, weighs 29 pounds and is about 1.8 m tall.

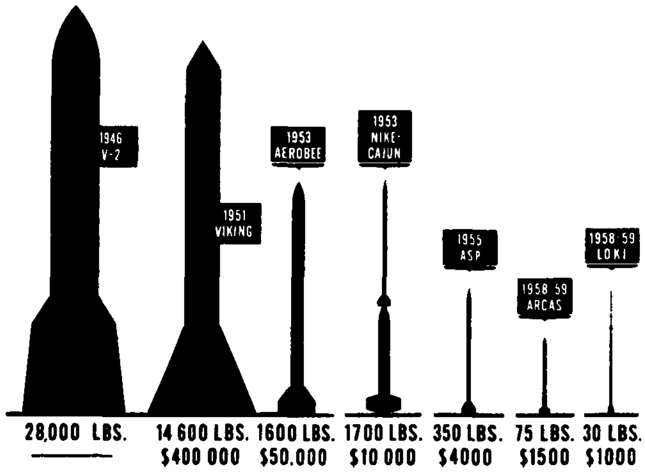

Fig. 5. Some of the upper-atmosphere research rockets used in the United States since 1946.

The dart has an inner diameter of about 3 cm, and the length of the payload contained is approximately 50 cm. For the network firings it was filled with 1 to 2 pounds of metalized nylon chaff having a diameter between 0.2 and 0.5 mm, which was ejected at the top of the rocket trajectory and tracked by radar. Theoretical computations by Barr [3] indicate that 0.3-mm nylon chaff tracks the wind practically instantaneously below 60 km, and no correction to the wind as measured by the radar needs be made if one is satisfied with a wind speed error of less than 5 mi/h. An automatic track of the chaff trajectory from about 61 km to 28 km is seen in fig. 7. The Loki II booster accelerates very rapidly and the rocket is therefore largely insensitive to low-level winds. The Loki II has been fired in winds in excess of 50 mi/h.

Insensitivity to low-level winds is unfortunately not so in the case of the Arcas rocket (fig. 8), which was and still is the workhorse with respect to the meteorological rocket network firings. The Arcas is a one-stage rocket weighing, with payload, 77 pounds; it is approximately 2.3 meters long and carries a payload of roughly 12 pounds, consisting of a metallized silk parachute 4.5 meters in diameter and a radiosonde (fig. 9). The latter is essentially the AN/AMT-4 radiosonde which was modified by the US Army Signal Missile Support Agency to accommodate a tiny 250-micron bead thermistor,

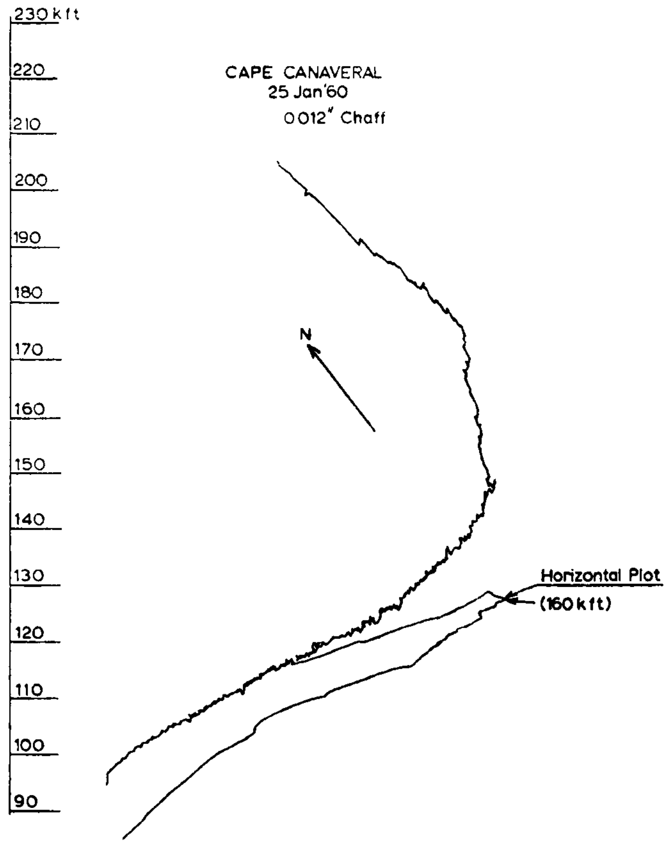

Fig. 7. Horizontal and vertical track of chaff as measured by radar (plotting board record). Numbers at left represent thousands of feet elevation.

which is aluminized to decrease the radiation error (fig. 10). If the bead is perfectly aluminized, the radiation error at 50 km should not exceed about 1° C [4, 5]. Unfortunately, the aluminization is not always perfect and therefore the error is usually larger, but should not exceed 5° C.

An interesting phenomenon which is illustrated in figs. 11 and 12 occurs from time to time and is not associated with the electronic circuitry within the sonde. These are the so-called "spikes" appearing on the temperature trace. Fig. 11 shows the record of the bead thermistor in a balloon-borne sonde, and depicts the temperature spikes most clearly. As can be seen, the spikes start from the base (left edge) of the record and extend out to higher temperatures. Thus, the left edge of the record is the correct temperature (to be adjusted for radiation and dynamic heating). Personnel of the US Army Missile Support Agency believe, after some experimentation with the

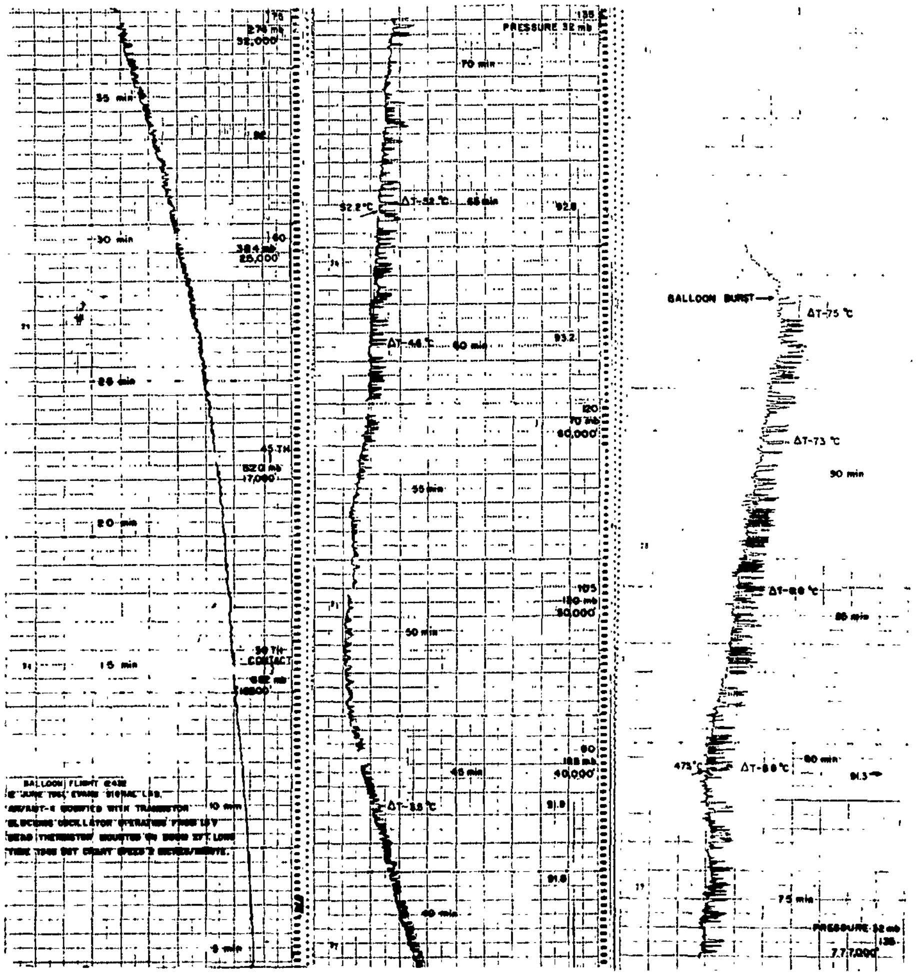

Fig. 11. Temperature record of an AN/AMT-4 radiosonde with bead thermistor carried on a balloon to approximately 30 km. The thermistor was mounted at the end of a 60-cm-long boom, extending sidewards from the radiosonde.

location of the bead thermistor, that the spikes are caused by heat flow coming from the relatively thin support wires of the bead while the sonde is swinging. It is felt, however, that more data have to be collected for a conclusive answer. It should be mentioned here that in the "gamma" sonde the bead thermistor is installed in front of the sonde between the uppermost two wires seen in fig. 9.

The rocketsonde, at the present time, measures the temperature only; the wind is determined by radar tracking of the metallized parachute.

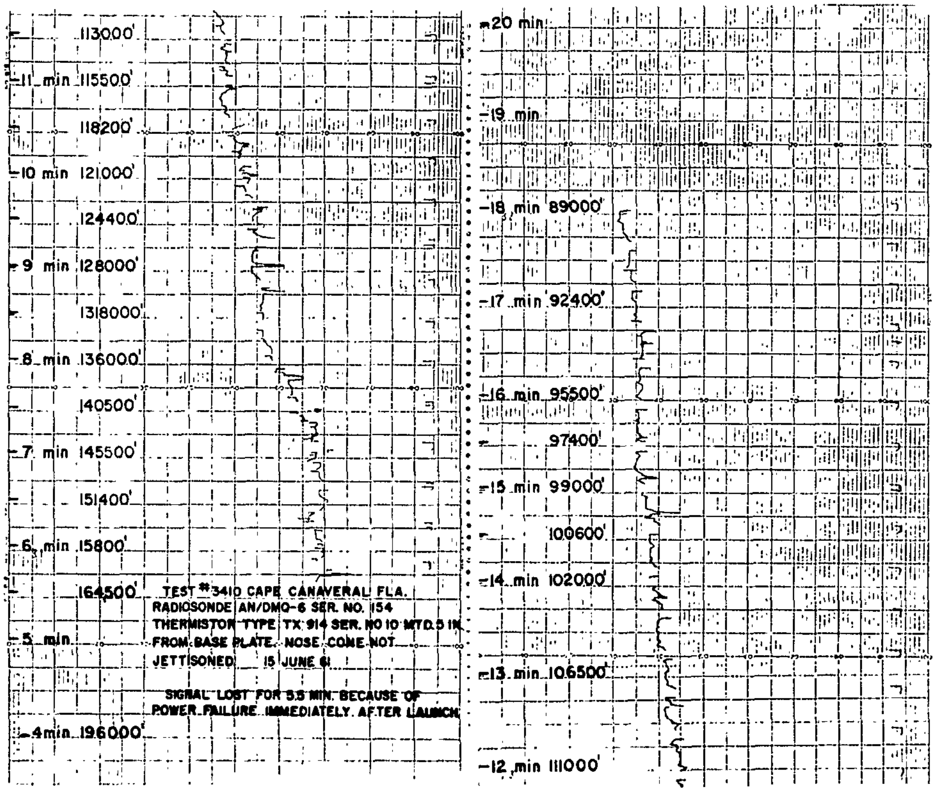

Fig. 12. Temperature records of a bead thermistor carried on the experimental rocketsonde AN/DMQ-6. (For installation of thermistor, see fig. 27.)

There is another payload, besides the rocketsonde, which has been extensively tested and which was also used in some meteorological rocket network firings. This is the "Robin" (fig. 13), developed under contract by the US Air Force. It is a one-meter-diameter mylar sphere with a metallized corner reflector inside. The balloon is pressurized and remains inflated down to about 27 km. While the wind is determined by radar tracking, the density of the air is computed from the change of fall velocity.

4. Results

So far, roughly 700 rocket flights have been carried out during the rocket network operation since its initiation in October 1959 when the first pilot firings were carried out at Point Mugu, Fort Churchill, and Fort Greely.

Theoretical investigations have indicated that, in addition to the chaff (as already mentioned), the parachute and the Robin are good wind sensors below 60 km, and in most cases do not need any correction if a wind-velocity accuracy of $\pm$ 5 mi/h is tolerated. Simplified computations on the wind-tracking ability of parachutes have been carried out by personnel of NASA, and an error analysis concerning wind and density as measured by the Robin have been carried out by personnel of the Air Force Cambridge Research Laboratories. The latter believe that the density can be determined to an accuracy of 2 to 3 percent.

Some experiments concerning the comparison of the various wind sensors have been conducted. These tests, in which the different wind sensors (chaff, parachute and Robin balloon) were released within about one hour, yielded that the difference of wind values as measured with these instruments is within the limits of the time variability of the wind in these altitudes.

This time variability was determined from limited wind measurements using the Loki chaff method at Cape Canaveral, Florida, on nine days during July and August 1960. The results of these limited data are shown in figs. 14 and 15. The various pairs of rockets from which the time variability of the wind was determined were fired within a time period of, on the average, 40 minutes (with 20 and 60 minutes as the limits). As can be seen, the wind variability increases with altitude from about 25 to 65 km, reaching approximately 8m/sec, or 18 mi/h. The direction variability varies from 5° at 28 km which is within the accuracy of the measuring method to about 25° at 60 km. Above this level it decreases again somewhat, which is not too significant in view of the limited amount of data available.

The changes of wind speed and direction over Pt. Mugu, California, in the course of 17 months are illustrated in fig. 16 [6]. This shows the summerly east and winterly west wind regimes with up to 250 knots wind speed at around 45 to 65 km. It shows, furthermore, chaotic and weak winds during spring and fall and a temporary breakdown in the upper flow late in January.

Fig. 17 shows in component presentation the winds of the months of June, July, August, and September over White Sands, New Mexico. The small N-S components are evident; also, the transition in September from the summer easterly to the winter westerly regime at high levels should be noted. Below 25 km the summer regime is still predominant.

Making extensive use of the meteorological network data, Battan [7] composed a picture of the global atmospheric circulation up to 100 km with time (fig. 18) and space (fig. 19) which shows the strong westerly jet in winter at around 70 km, and a somewhat weaker easterly jet in summer at around 55 km. While fig. 18 shows an indication of easterly winds in mid-winter between about 35 and 55 km, this break in the winterly west wind

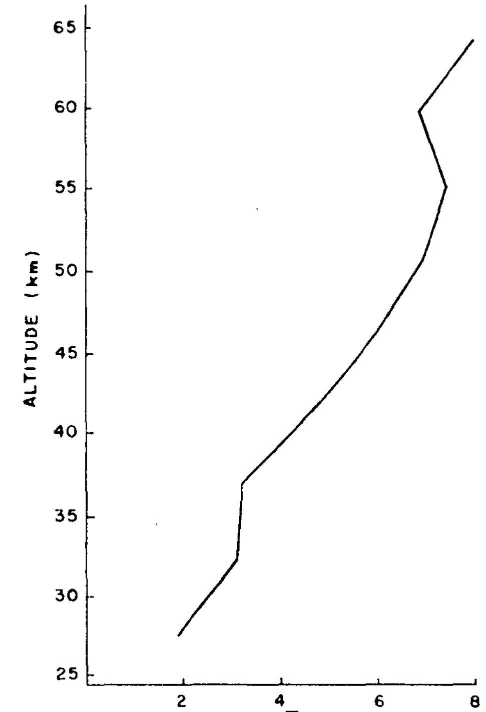

Fig. 14. Vertical distribution of short period wind speed variability at Cape Canaveral, Florida, in summer.

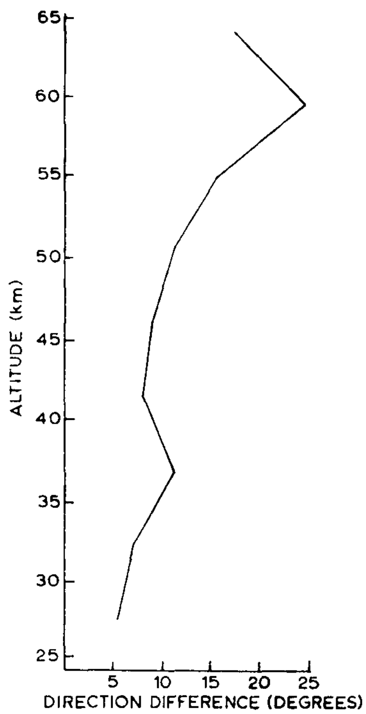

Fig. 15. Vertical distribution of short-period wind direction variability at Cape Canaveral, Florida, in summer.

circulation is clearly shown in figs. 20, 21 and 22, which Keegan [8] derived from rocket network and balloon data of the winters of 1960 (figs. 20 and 21) and 1961 (fig. 22). Figs. 20 and 21 demonstrate the similarity between the wind patterns at opposite sides of the North American continent. The wind reversal centered at 30 km in late January and early February dominates both cross sections. The greatest measured wind change occurred in the layer between about 30 and 40 km. There the zonal wind changed from roughly 40 to 60 m/s West to 10 to 30 m/s East. By 5 February the wind profiles above both stations had returned to "normal."

WIND AND TEMPERATURE MEASUREMENTS

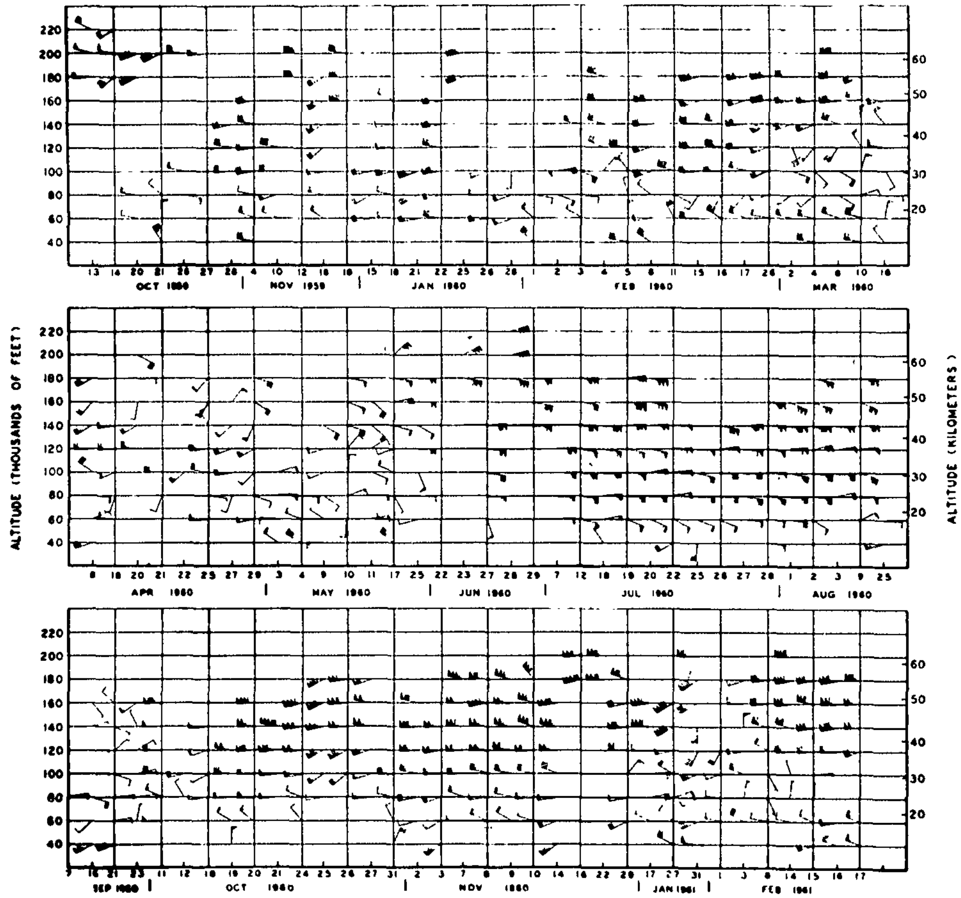

Fig. 16. Plot on a nonlinear time base of meteorological rocket winds in knots, at Point Mugu, California (according to J. E. Masterson, *et al*). Each flag represents 50 knots and each half barb 5 knots.

In contrast to 1960 when one prolonged disturbance affected the high levels, a series of disturbances occurred in the winter of 1961 (fig. 22). On 17 January the westerly winds reached a maximum at 60 km with 120 m/sec, and easterly winds were reported as high as 50 km on the 20th. Unfortunately, data for the following days are missing so that the extent and magnitude of these easterly winds could not be determined. A second period of easterlies occurred early in February between 35 and 55 km. The centers of these easterlies in the winter of 1961 were located at higher altitudes and they also were of shorter duration than those of the previous winter. On the

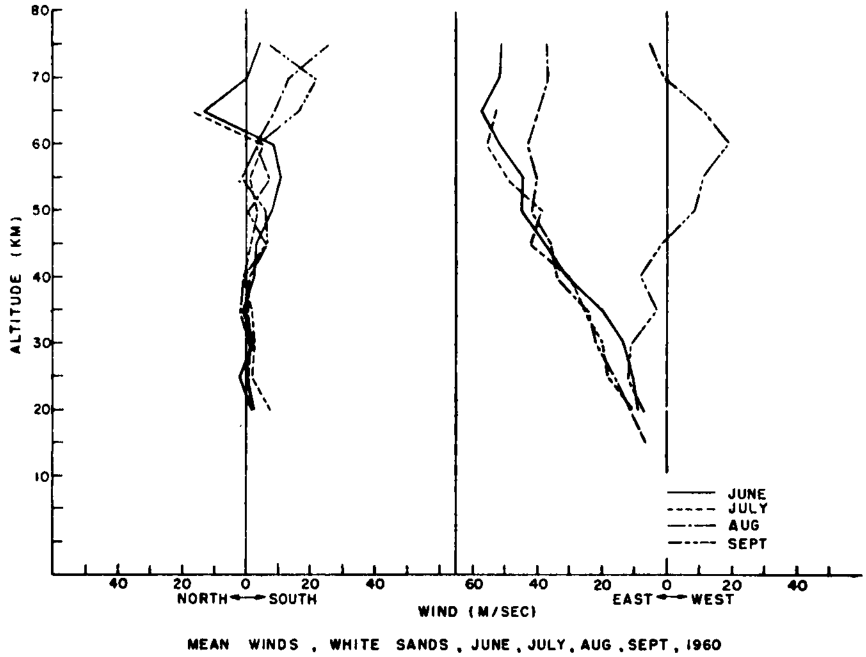

Fig. 17. Monthly mean wind velocity components, White Sands, New Mexico.

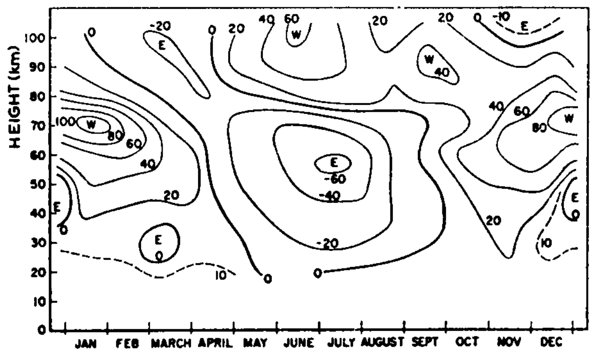

Fig. 18. Time cross section of the zonal wind between latitudes of 30 and 40 degrees (speed in m/sec) (according to E. S. Battan).

whole, the upper-air circulation in the winter of 1961 was apparently less settled than that in 1960.

In a subsequent paper in this symposium, Messrs Teweles and Finger discuss in more detail synoptic studies based on rocketsonde data.

Fig. 23 shows the temperature profile over White Sands, New Mexico, during summer and fall, 1960. Fig. 24 shows the temperature profile over

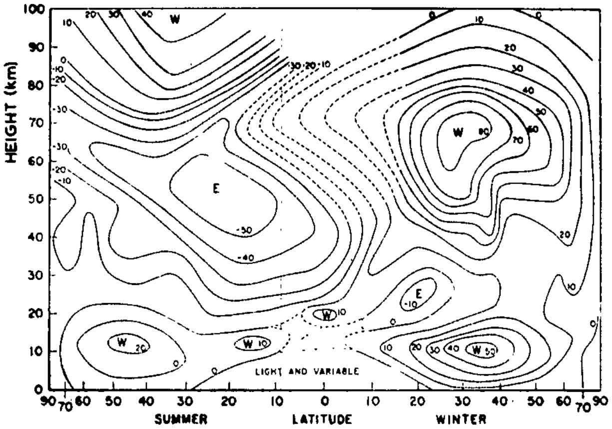

Fig. 19. Average zonal wind components (speed in m/sec) (according to E. S. Battan).

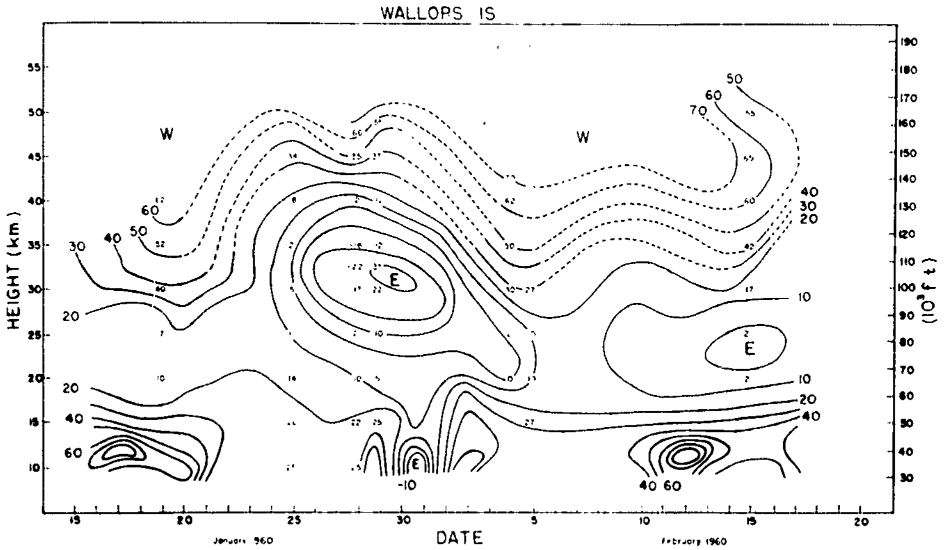

Fig. 20. Zonal wind speed (m/s) over Wallops Island, Virginia, during the winter of 1960 (according to T. J. Keegan).

Fort Churchill, Canada, during August and November. The striking features of these figures are that there is very little difference between the temperature profiles over White Sands of summer and fall between 25 and 50 km, but that the difference in the temperature profiles of August and November over Fort Churchill is very great. At around 40 km the difference is more than 30° C.

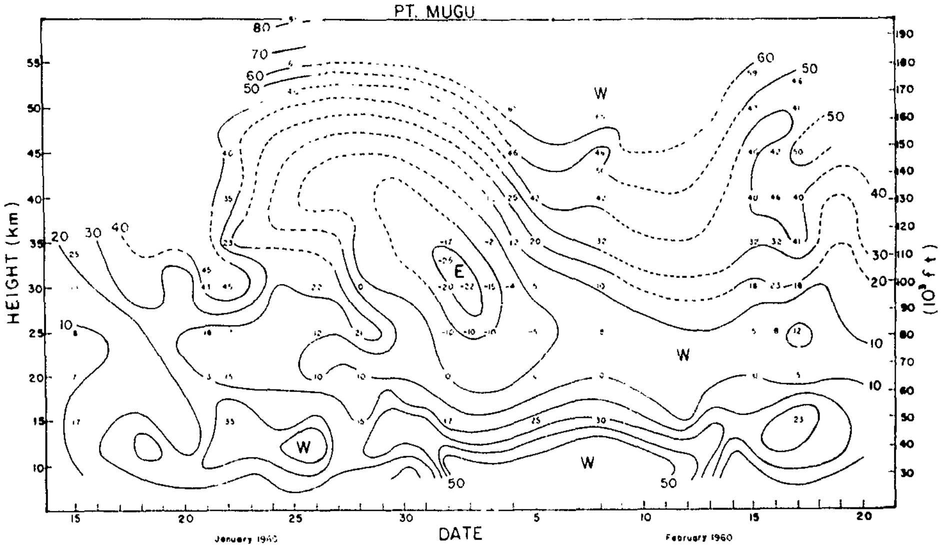

Fig. 21. Zonal wind speed (m/s) over Point Mugu, California, during the winter of 1960 (according to T. J. Keegan).

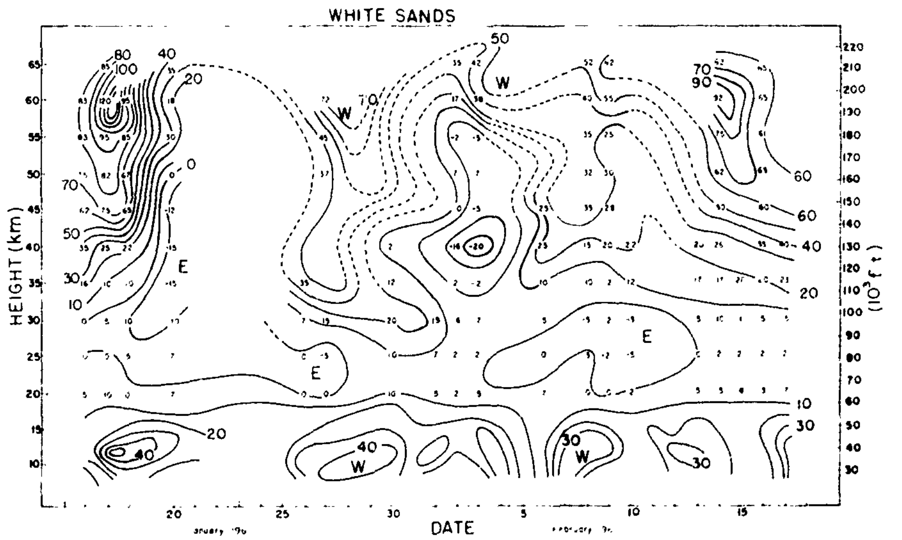

Fig. 22. Zonal wind speed (m/s) over White Sands, New Mexico, during the winter of 1961 (according to T. J. Keegan).

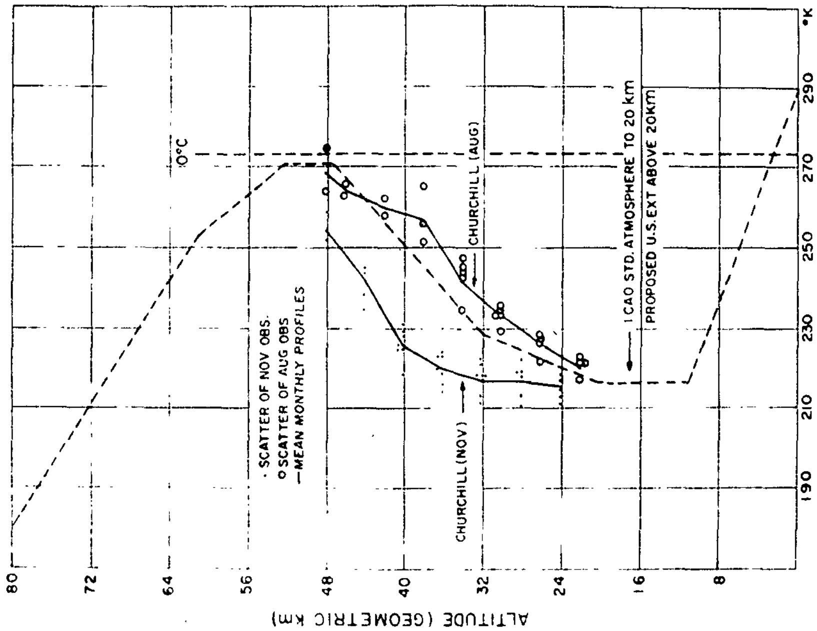

Fig. 24. Temperature profile over Fort Churchill, Canada, during August and November 1960.

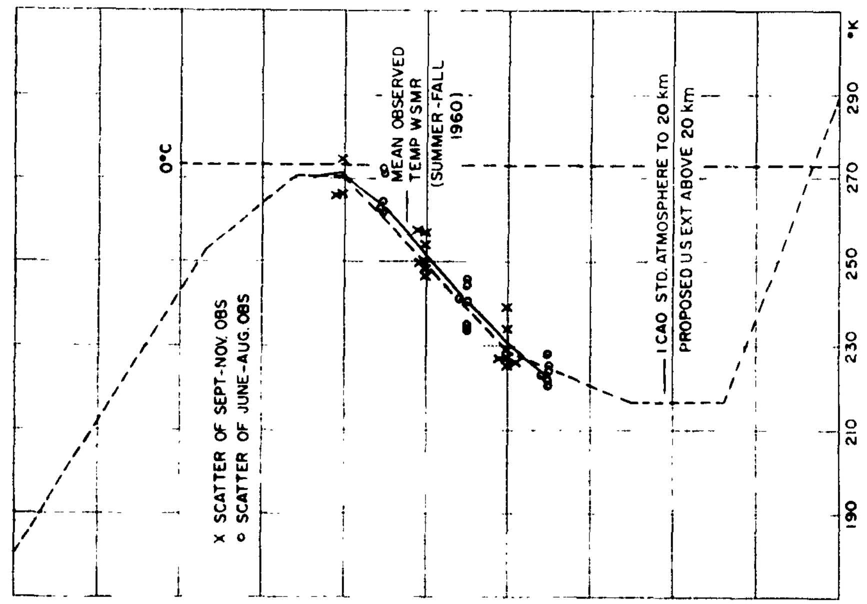

Fig. 23. Temperature profile over White Sands, New Mexico, during summer and fall 1960.

Using the temperature measurements made by the rocketsondes and the pressure at 30 km as determined by balloon ascents, it was possible to draw, for the first time, average 1-mb maps for summer and winter over the American continent, which are shown in figs. 25 and 26.

5. Future plans

While the US Meteorological Rocket Network is considered to be still in the research and development status, the firings will become gradually routine and the entire organization will then probably be taken over by the US Weather Bureau. It is hoped that more stations in the northern hemisphere and also in the southern hemisphere will join us so that we shall have, in the not too distant future, a global meteorological rocket network making routine or quasi-synoptic (considering the phase of tidal winds) rocket ascents as has been done for many years with balloons.

In the meantime, the improvement of the present sensors and the development of new sensors are progressing. The US Army Signal Research and Development Laboratory, Fort Monmouth, has already successfully tested the previously mentioned Rocketsonde AN/DMQ-6. (Fig. 27). It carries in addition to a bead thermistor, a hypsometer, shown in fig. 28, which yielded very encouraging results in the few test flights carried out so far.

The AN/DMQ-6 was developed in order to be independent of the radar equipment on the missile ranges. Using on the ground the AN/GMD-2 system, the altitudes of the sonde can be determined from the range and elevation angle. The AN/GMD-2 system is essentially an AN/GMD-1 system plus a range-determination accessory.

Also in the design status at the US Army Signal Research and Development Laboratory and its contractor is a four-channel parallel telemetering rocketsonde AN/DMQ(XE-1) (fig. 29). With this sonde the sensors do not have to share the telemetering system, but four sensors can telemeter simultaneously. A few sensors considered for this sonde are also shown in fig. 29.

While these instruments are being designed to fit the Arcas or a similar rocket, small instrument packages for measuring temperature, density, and pressure and fitting the Loki rocket are also being developed and some have already been successfully test-flown.

Thus, the instrument designers have their hands full in developing more and better sensors to be flown in the future meteorological network rockets. However, the research meteorologist will not be idle. He must analyze all the continuously incoming data, which will be increasingly better in quality

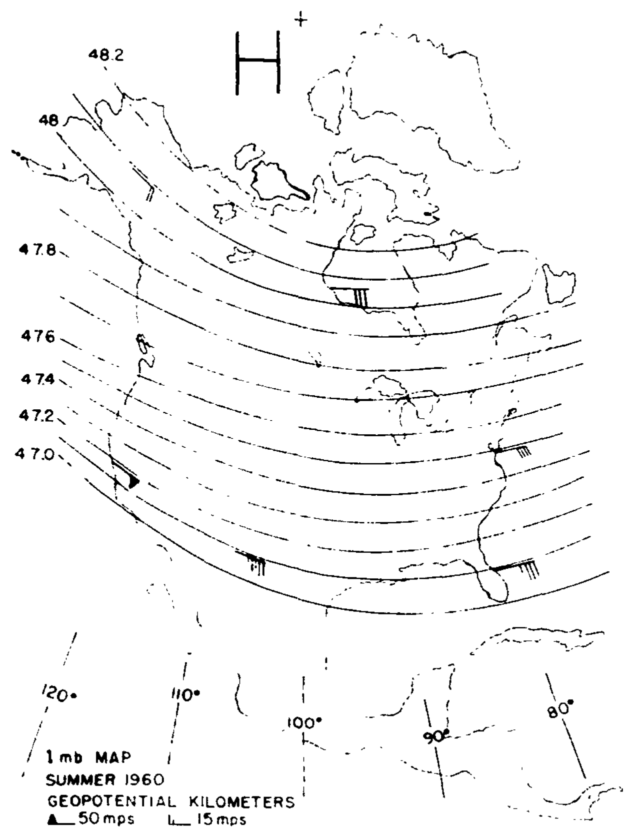

Fig. 25. One-mb map, summer 1960. Height contours are in geopotential kilometers.

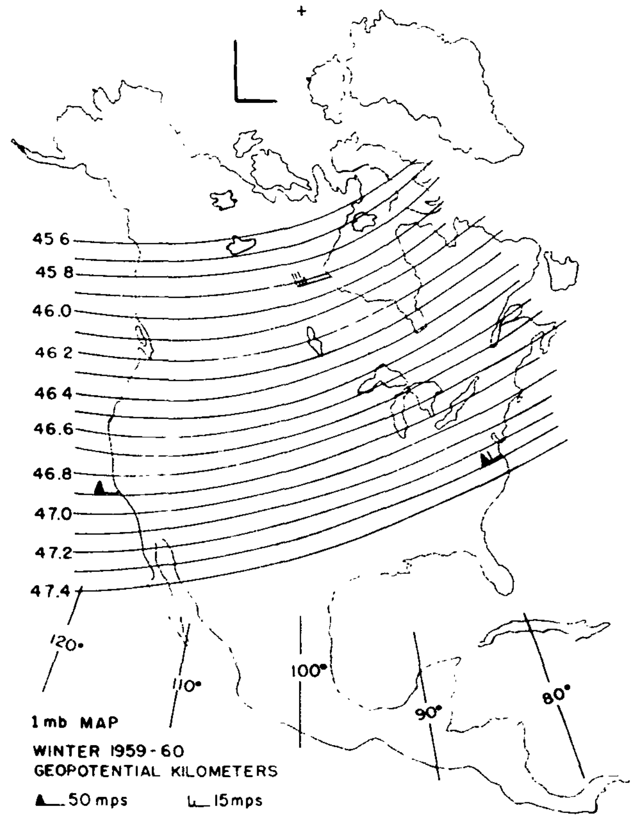

Fig. 26. One-mb map, winter 1959–1960. Height contours are in geopotential kilometers.

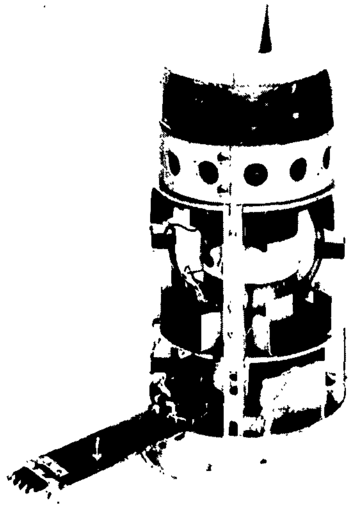

Fig. 27. AN/DMQ-6 rocketsonde with installed hypsometer and frame holding bead thermistor.

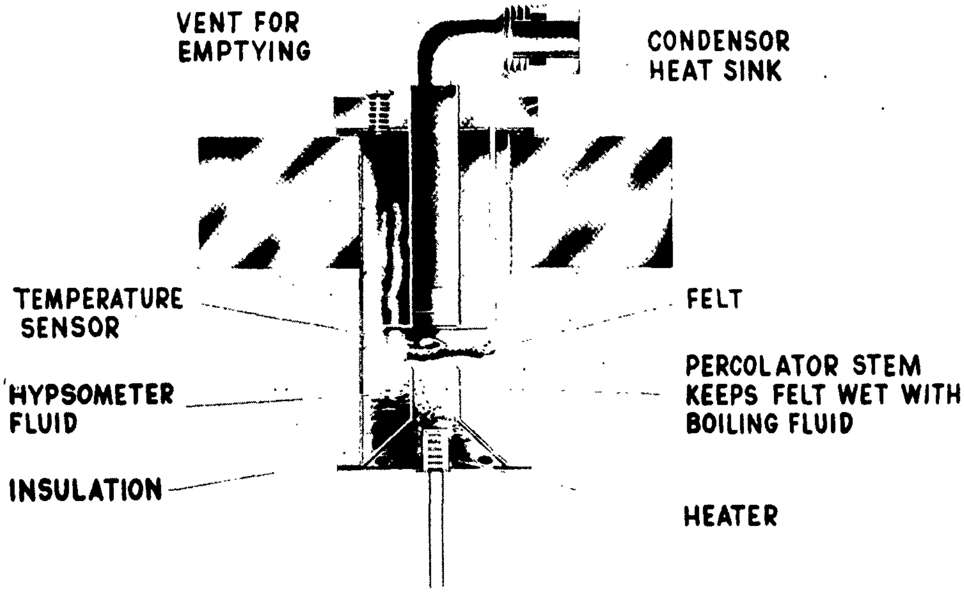

Fig. 28. Cross section of hypsometer for the rocketsonde AN/DMQ-6.

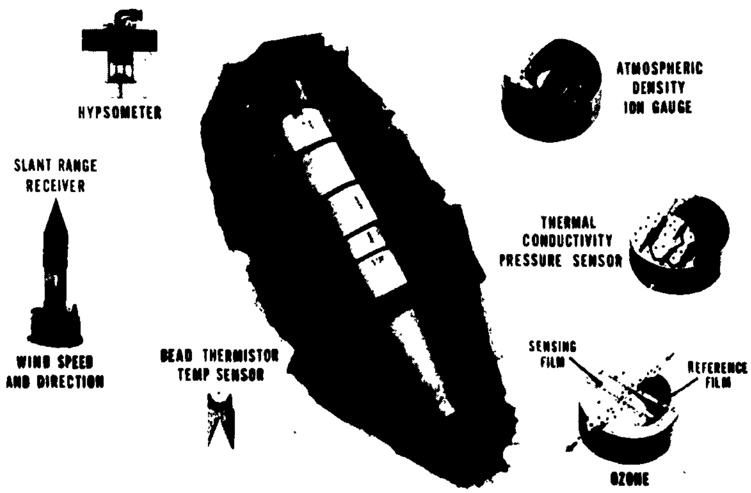

Fig. 29. Rocket Radiosonde AN/DMQ (XE-1).

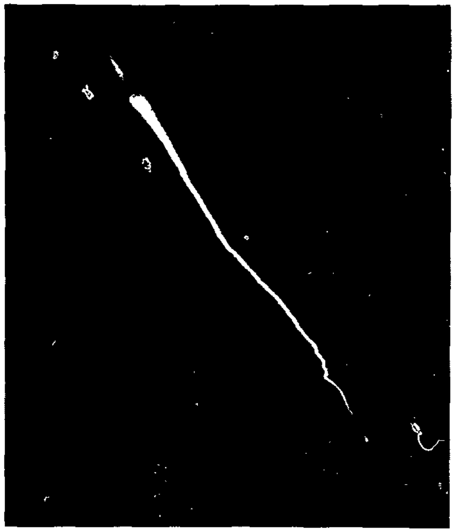

Fig. 30. Exhaust trail of a rocket just after its formation between about 60 and 110 km.

Fig. 31. The same trail as in fig. 30 about three minutes later.

Fig. 32. Time exposure of the trail seen in figs. 30 and 31.

and considerably more numerous. At the same time, while the network is sending rockets and radiosondes up to about 70 km, more and more on a routine basis, he must look forward and upward. The network should spread not only laterally, but also vertically. The fact that very interesting phenomena occur at the layers adjacent to the level covered by the meteorological rocket network may be seen in figs. 30, 31, and 32, which are self-explanatory. Winds of more than 500 mi/h and shears of the order of 10^{-1} per sec have been determined. In order to find out the extent of these phenomena, some kind of synoptic investigations of these layers also will have to be carried out. How this can be done is described by Professor Blamont in a subsequent paper in this symposium.

Much has been accomplished in the past two years in setting up the network. We are sure that in only a few years meteorologists will have a comprehensive, global picture of the atmosphere from the ground up through the mesosphere.

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